

OPTIMIZATION OF MOTOR AND GEARBOX FOR AN ULTRA LIGHT ELECTRIC VEHICLE

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ABSTRACT

The integrated design of the drivetrain of a single person ultra light electric vehicle powered by batteries is optimized towards high efficiency and low mass. The drivetrain of each front wheel consists of an outer rotor permanent magnet synchronous motor (PMSM), a gearbox and the power electronics with converter and control print. The complete drivetrain is optimized for the New European Driving Cycle and the Federal Test Procedure. For the optimization of the complete drivetrain analytical models are used to calculate the losses and the efficiency. The analytical models are fast, and useful for designing a good PMSM in combination with a gearbox. The optimization of the drivetrain over the driving cycles makes it possible to choose the optimal combination of motor and gearbox for different gear ratios in order to have high efficiency and low weight. Comparing a single-stage gearbox with a two-stage gearbox, a single-stage gearbox has a higher efficiency, but also a higher weight than a two-stage gearbox with the same properties. The optimization of the dynamic behavior of the drivetrain over the driving cycles yields a compromise between the total efficiency and the total mass of the drivetrain. The optimum choice will depend on the intended use of the vehicle (drive cycle).

INTRODUCTION

Electric vehicles (EVs) are back in the street view, but most of them have a large battery pack, which can be noticed in the price of the vehicle. Therefore, we want to design an ultra light EV. This ultra light EV is a single person battery powered EV mainly for commuting purposes in the city and the suburbs. The drivetrain of the ultra light EV is optimized towards maximal average efficiency over a drive cycle and minimal weight of the total drivetrain. Due to the highly efficient drivetrain, less batteries are needed for the same driving range. Furthermore, the total weight of the car can be reduced and also the total cost of the vehicle. The goal is to have a transportation method with less energy consumption than a commercial EV but yet much faster, more comfortable and safer than a bike.

ULTRA LIGHT ELECTRIC VEHICLE

The tri-cycle battery powered ultra light EV, mainly for commuting purposes, has two driven and steering front wheels. The maximum speed of the EV is 70 km/h and a range of 100 km has to be covered. The total curb weight is about 100 kg (batteries included). The battery pack of the EV consists of Lithium Polymer (LiPo) batteries with a high energy to weight ratio: 20 Ah, 96 V and 11 kg. The dimensions of the car are: a total length of 2200 mm, a total width of 1200 mm and a total height of 1300 mm. Fig. 1 shows the ultra light EV.



Figure 1 Ultra light electric vehicle.

DRIVETRAIN OF EACH FRONT WHEEL

The highly efficient drivetrain for each front wheel of the ultra light EV consists of: a gearbox, a brushless (BL) DC motor and power electronics (PE). In Fig. 2 the drivetrain of each front wheel of the EV is shown.

The battery provides the power stage of each BLDC motor with current. The power stage contains a DC-DC converter which is connected to the three stator coils of the BLDC motor. Each of the stator coils is powered by a half bridge, two of them contain a current sensor to measure the phase current. The two phase currents are measured by the control print. This control print is fed by a flyback converter on the power stage. In order to determine the exact rotor position of the BLDC motor, Hall sensors are mounted on the motor. The signal from the Hall sensors is fed first to the control print and then to the power stage to switch on the correct transistors to drive the motor. On the steer of the EV, two handles [1] are mounted, a drive handle and a brake handle. The signals of the handles are fed to the control print. With the enable button the power electronics can be switched on or off. The driving direction of the EV can be reversed by the torque direction button. At the front wheel side, the BLDC motor is coupled with a gearbox in order to reduce the speed and increase the torque of the motor on the front wheel.

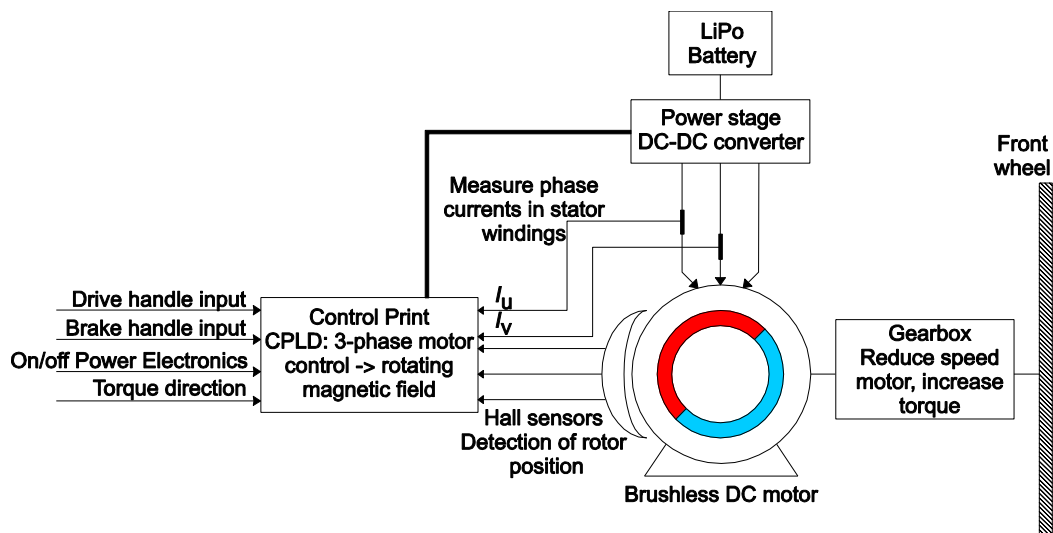


Figure 2 Drivetrain for each front wheel of the ultra light electric vehicle.

INTEGRATED DESIGN

As shown in Fig. 2, the drivetrain of each front wheel of the ultra light EV consists of a gearbox, a BLDC motor and PE. An optimized analytical design for the outer rotor permanent magnet synchronous motor (PMSM) is implemented in combination with an improved gearbox. The objective function of the optimization is shown in Fig. 3.

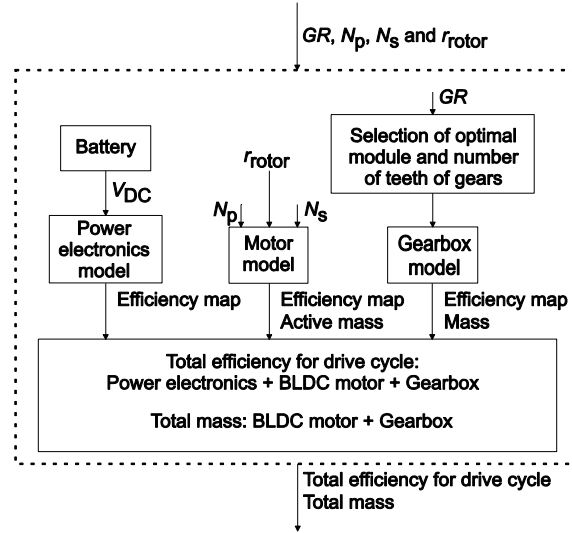


Figure 3 Objective function of the optimization, executed for GR s: $\frac{1}{2} - \frac{1}{7}$ single-stage gearbox and $\frac{1}{7} - \frac{1}{14}$ two-stage gearbox, N_p : 3 – 8, N_s : 9 – 18 and r_{rotor} : 0.025 – 0.120 m.

The input parameters of the objective function in Fig. 3 are: the gear ratio (GR), the number of pole pairs (N_p), the number of stator teeth (N_s) and the outer rotor radius of the motor (r_{rotor}). The output parameters are the total average efficiency for a drive cycle and the total mass of the complete drivetrain. The objective function contains three analytical models (PE model, motor model and a gearbox model) which will be explained in the following paragraphs.

The optimized parameters of the outer rotor PMSM are: the outer rotor radius, the number of stator teeth and the number of pole pairs. The losses and the efficiency of the PMSM are calculated. Moreover the total active mass of the motor is calculated.

A single-stage and two-stage gearbox model is implemented for different gear ratios. The optimization parameters for the gearbox are: the number of teeth, the module of each gear combination and the total mass of the gearbox. The gear ratios that were investigated are for the single-stage gearbox: $\frac{1}{2} - \frac{1}{7}$ and for the two-stage gearbox: $\frac{1}{7} - \frac{1}{14}$. Furthermore for the single-stage gearbox, the optimization was also executed for a direct drive combination, thus without the usage of a gearbox. Each of the motor and wheel gear combinations are able to transfer the required peak torque. Fig. 4 shows the mass for several possible gears (motor and wheel gear combinations) for a single-stage gearbox with a gear ratio of $\frac{1}{2}$. Each of the markers defines a combination of motor and wheel gears with a different module and/or different teeth numbers. From Fig. 4, it is clear that the combination of 25 teeth at motor side and 50 teeth at wheel side with module 1, gives the lowest total mass for the different gear combinations. This approach was used for each gear ratio. It is a sub optimization shown in the objective function of Fig. 3.

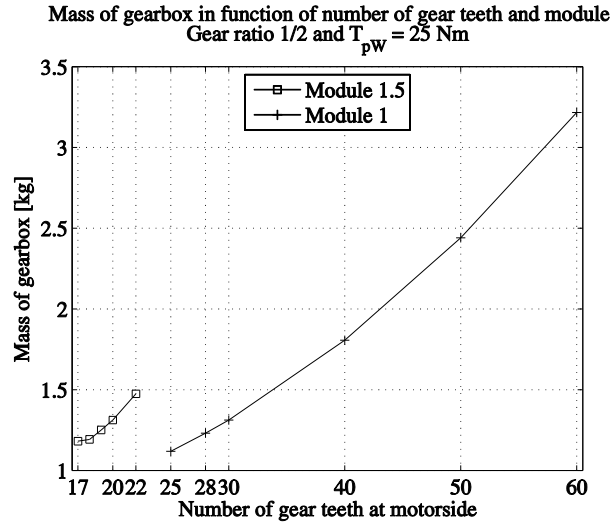


Figure 4 Mass of the single-stage gearbox in function of number of teeth and module for a gear ratio of $1/2$.

The power electronics model calculates the losses and the efficiency of the power electronics. The input parameter is the DC bus voltage of the battery (V_{DC}).

The PMSM and the gearbox are optimized for the New European Driving Cycle (NEDC) [2] and the Federal Test Procedure (FTP) [3], [4]. The NEDC and FTP driving cycle are shown in Fig. 5, but due to the maximum speed of 20 m/s of the vehicle, the NEDC and FTP are cut off at that specific speed.

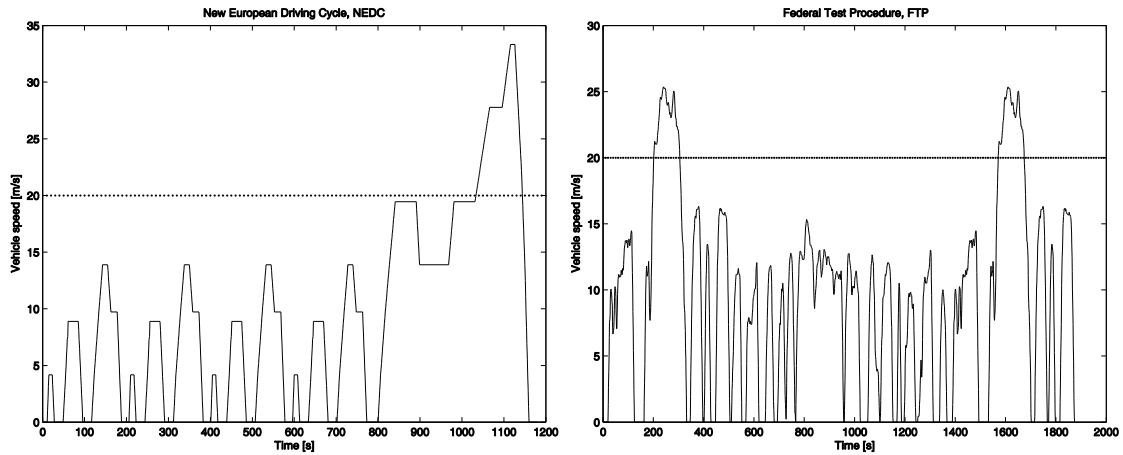


Figure 5 a) New European Driving Cycle, and b) the Federal Test Procedure. The dashed line is the maximum speed of the ultra light electric vehicle.

The average speed over the NEDC is 33.6 km/h and the maximum speed is 120 km/h. The total distance of the NEDC is 11.017 km and the duration is 1180 s [2]. The average speed over the FTP is 34.2 km/h and the maximum speed is 91.09 km/h. The total distance of the NEDC is 17.787 km and the duration is 1874 s [3], [4].

The goals of the objective function in Fig. 3 are a minimization of total weight and a maximization of the total average efficiency of the complete drivetrain for the different driving cycles, consisting of the power electronics, the PMSM and the gearbox.

RESULTS

The objective function of Fig. 3 is executed for several GRs and for a range of the motor parameters N_s , N_p and r_{rotor} . For each combination of input parameters, the total mass and average efficiency of the complete drivetrain are computed for the different driving cycles.

In Fig. 6a the total mass for a complete drivetrain with a single-stage gearbox, N_p : 6 and N_s : 9 is shown and in Fig. 6b the total mass for a complete drivetrain with two-stage gearbox is shown. Note that the total mass of the complete drivetrain is the same for each driving cycle, it only depends on the gearbox version (single-stage or two-stage gearbox).

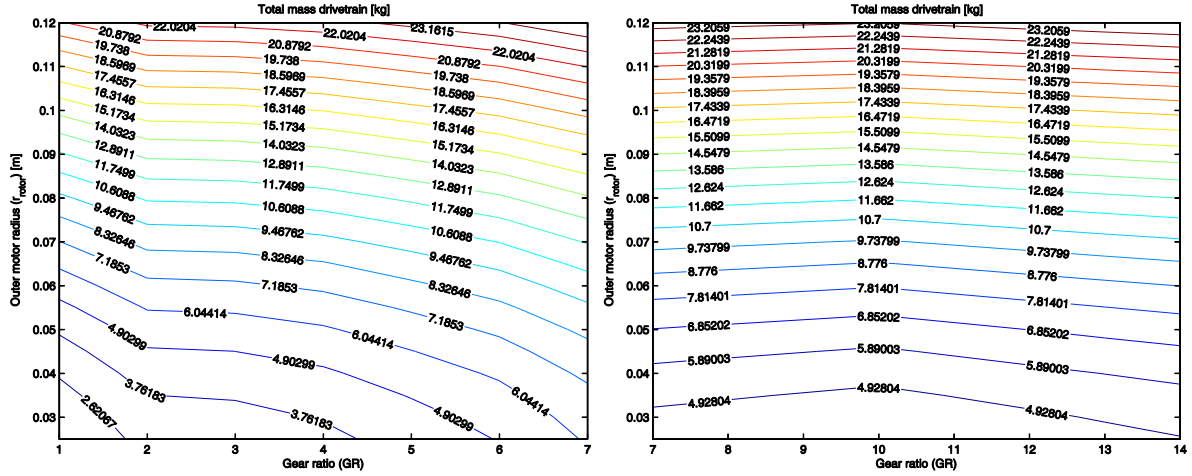


Figure 6 Total mass for the complete drivetrain with N_p : 6 and N_s : 9 a) drivetrain with single-stage gearbox, and b) drivetrain with two-stage gearbox.

The average efficiency optimized for the NEDC and the FTP for a complete drivetrain with a single-stage gearbox with N_p : 6 and N_s : 9 is shown in Fig. 7.

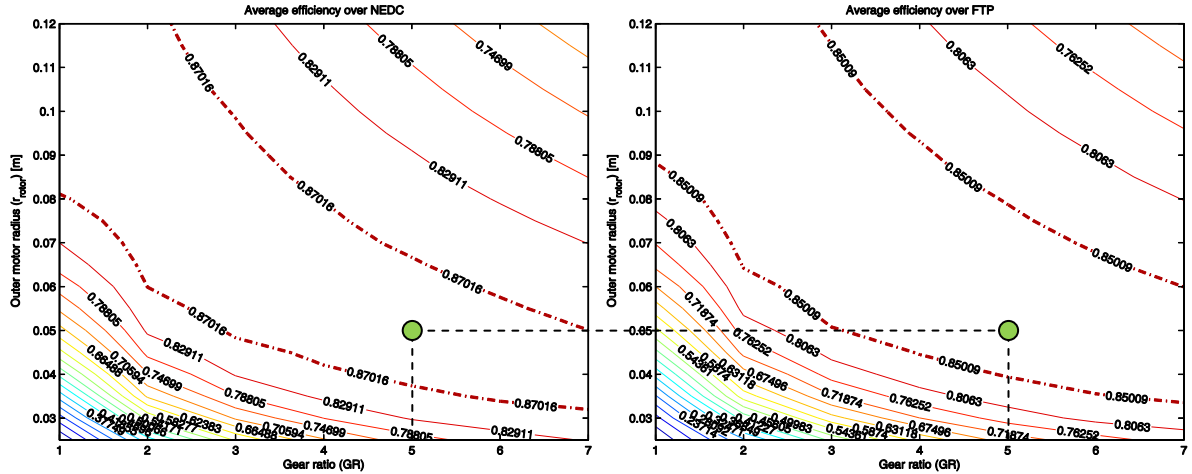


Figure 7 Total average efficiency for the complete drivetrain with N_p : 6 and N_s : 9 and a single-stage gearbox a) for the New European Driving Cycle, and b) for the Federal Test Procedure. The region within the dash-dot lines shows the combinations of GR and outer rotor radius that yield the highest average efficiency.

A very important observation in Fig. 6a combined with Fig. 7 is that with an increasing GR of the single-stage gearbox, the outer rotor radius should decrease to get a higher average efficiency of the complete drivetrain.

For a low GR of $\frac{1}{2}$, the highest average efficiency is obtained with a motor of double radius compared to a high GR of $\frac{1}{7}$.

In Table 1 the results for the optimization of the complete drivetrain with a single-stage gearbox are mentioned. Note that in Table 1 the optimal results for the optimization of the complete drivetrain are also mentioned.

Properties	NEDC	NEDC	FTP	NEDC optimum	FTP optimum
25 Nm, single-stage gearbox	$GR: \frac{1}{5}, N_p: 6,$ $N_s: 9,$ $r_{rotor}: 0.060m$	$GR: \frac{1}{7}, N_p: 6,$ $N_s: 9,$ $r_{rotor}: 0.040m$	$GR: \frac{1}{5}, N_p: 6,$ $N_s: 9,$ $r_{rotor}: 0.060m$	$GR: \frac{1}{4}, N_p: 6,$ $N_s: 9,$ $r_{rotor}: 0.045m$	$GR: \frac{1}{4}, N_p: 7,$ $N_s: 12,$ $r_{rotor}: 0.045m$
Av. efficiency	87.84 %	88.06 %	87.13 %	87.73 %	85.74 %
Total mass	8.11 kg	7.41 kg	8.11 kg	5.29 kg	5.22 kg
Driving range	115.77 km	116.06 km	128.20 km	115.63 km	126.16 km

Table 1 Optimization results of the complete drivetrain with single-stage gearbox.

For a drivetrain with a two-stage gearbox, the total average efficiency optimized for the NEDC and the FTP with $N_p: 6$ and $N_s: 9$ is shown in Fig. 8.

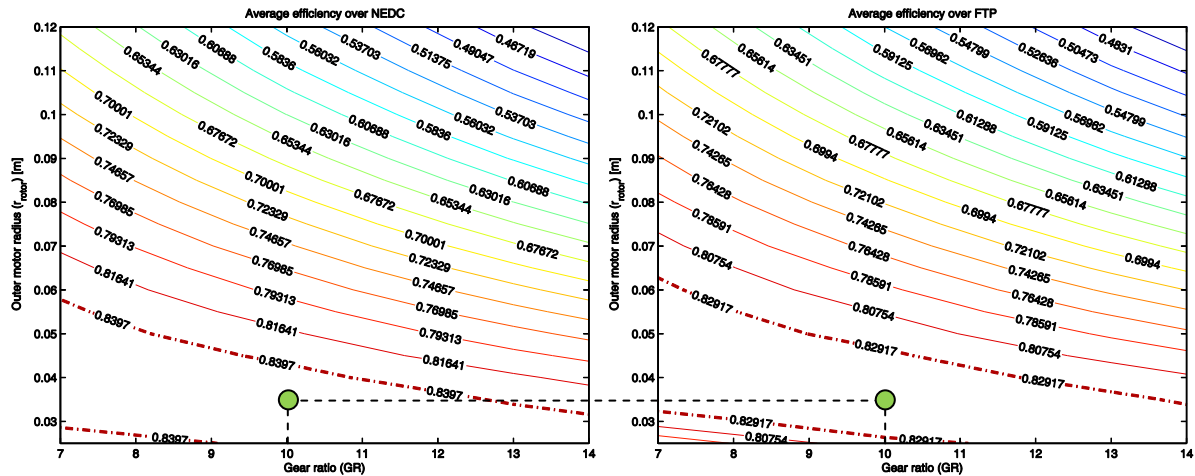


Figure 8 Total average efficiency for the complete drivetrain with $N_p: 6$ and $N_s: 9$ and a two-stage gearbox a) for the New European Driving Cycle, and b) for the Federal Test Procedure. The region within the dash-dot lines shows the combinations of GR and outer rotor radius that yield the highest average efficiency.

From Fig. 6b and Fig. 8 it is clear that the drivetrain with a two-stage gearbox gets highest average efficiency and a low total mass when a low GR in combination with a small outer rotor radius is selected.

In Table 2 the results for the optimization of the complete drivetrain with a two-stage gearbox are mentioned. Note that in Table 2 the optimal results for the optimization of the complete drivetrain are also mentioned.

Properties 25 Nm, two-stage gearbox	NEDC $GR: \frac{1}{10}, N_p: 6,$ $N_s: 9,$ $r_{\text{rotor}}: 0.035\text{m}$	NEDC $GR: \frac{1}{7}, N_p: 6,$ $N_s: 9,$ $r_{\text{rotor}}: 0.040\text{m}$	FTP $GR: \frac{1}{10}, N_p: 6,$ $N_s: 9,$ $r_{\text{rotor}}: 0.035\text{m}$	NEDC optimum $GR: \frac{1}{10}, N_p: 6,$ $N_s: 9,$ $r_{\text{rotor}}: 0.025\text{m}$	FTP optimum $GR: \frac{1}{10}, N_p: 6,$ $N_s: 9,$ $r_{\text{rotor}}: 0.030\text{m}$
Av. efficiency	85.66 %	86.30 %	84.85 %	85.00 %	84.33 %
Total mass	4.73 kg	5.64 kg	4.73 kg	3.97 kg	4.31 kg
Driving range	112.90 km	113.74 km	124.85 km	112.03 km	124.08 km

Table 2 Optimization results of the complete drivetrain with two-stage gearbox.

Compared to a drivetrain with a single-stage gearbox, $N_p: 6$, $N_s: 9$ and $r_{\text{rotor}}: 0.04$ m optimized for the NEDC, the highest total average efficiency of a drivetrain with a two-stage gearbox with the same properties ($N_p: 6$ and $N_s: 9$ and $r_{\text{rotor}}: 0.04$ m) is 1.76 % lower. Also the region of high average efficiency is smaller compared to a drivetrain with a single-stage gearbox.

A general conclusion for Fig. 7 and Fig. 8 is that for each GR a good combination with an outer rotor radius can be found in order to have a high average efficiency of the complete drivetrain and low mass, see the dash-dot line in Fig. 7 and Fig. 8.

CONCLUSIONS

Integrated design of the complete drivetrain will result in an optimal combination of motor and gearbox for that driving cycle. Furthermore, it increases the integration between the motor, the gearbox and the power electronics. This will result in a system that is more compact, lighter and more efficient than a drivetrain with “off-the-shelf components”. The optimum choice of motor combined with gearbox obviously depends on the intended use of the vehicle.

Comparing a single-stage gearbox with a two-stage gearbox, a single-stage gearbox has a higher efficiency, but also a higher weight than a two-stage gearbox with the same properties.

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